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(54) **Quadrature optical phase modulators for lightwave systems.**

(57) Optical communication methods and apparatus are disclosed for transmitting two or more optical signals with different optical carrier frequencies ($F_{01}$, $f_{c2}$) on a single optical fiber with high spectral efficiency. Each optical carrier is typically modulated with multiple modulated subcarriers. In one embodiment, an optical phase modulator provides cancellation of second order intermodulation products in each optical signal, thereby permitting the optical carrier frequencies to be spaced by $2f_{max}$, where $f_{max}$ is the maximum modulation frequency. In another embodiment, a single sideband optical phase modulator provides cancellation of second order inter-modulation products and one signal sideband, thereby permitting the optical carrier frequencies to be spaced by $f_{max}$. Quadrature optical phase modulators for simultaneous transmission of two independent baseband digital data signals or two independent subcarrier multiplexed signals are disclosed.

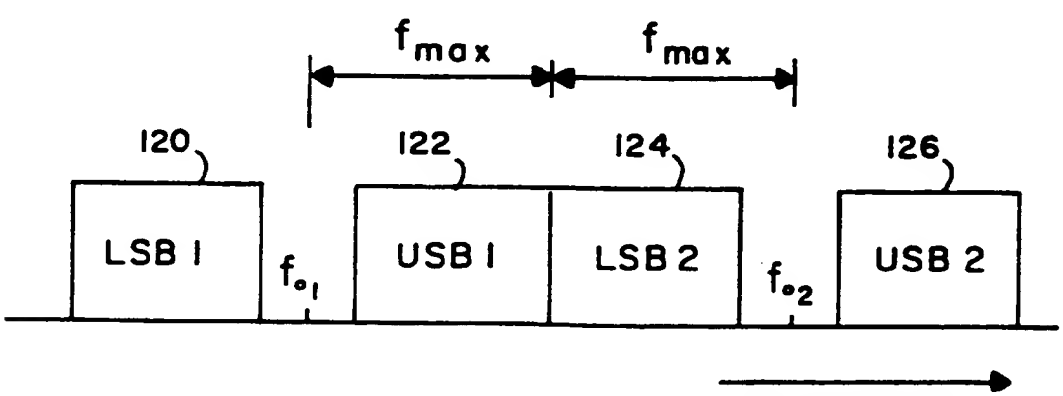


FIG.8

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This invention relates to optical communication systems wherein one or more modulated optical carriers are transmitted over a single optical fiber and, more particularly, to quadrature optical phase modulators and to optical communication systems which utilize the quadrature optical phase modulators.

Optical fiber transmission systems are being extensively used in the telephone network for long distance and interoffice trunk lines because of their wide bandwidth, small size and insensitivity to electrical interference. Conventional long distance optical transmission systems utilize time division multiplexed digital transmission. The maximum data rate available in commercial lightwave systems was for many years limited to 565 megabits per second, and has only recently been increased to 1.7 gigabits per second. A 565 megabits per second optical trunk line carrying 8000 voice channels is very cost effective for voice transmission.

Recently, efforts have been made in the telecommunications industry to utilize optical transmission systems in the local, or subscriber, loop between the central office and individual subscribers. The goal is to provide not only voice, but also data and video transmission over the optical fiber to every home and business. The video services are expected to include not only broadcast services but also switched video services which will enable each subscriber to select programming and movies from video libraries. An uncompressed digital video signal requires a data rate of about 100 megabits per second, and analog FM video requires a bandwidth of about 30 MHz. The 565 megabits per second system can carry only a few video channels.

Increased transmission bandwidth can be realized with coherent optical systems using multiple modulated optical carriers which are closely spaced in frequency. Coherent systems with multiple optical carriers have been disclosed by Shikada in "Multiplex Transmitting Method for Optical Heterodyne/Homodyne Detection Wavelength", Japanese patent publication No. 62-43231, 1987. In the Shikada system, one information channel is transmitted on each optical carrier, but N optical carriers can be utilized.

Subcarrier multiplexed (SCM) optical communication systems have also been proposed as a means for providing increased transmission bandwidth. A wideband signal composed of many frequency multiplexed carriers at either RF or microwave frequencies is used to modulate an optical carrier. The optical signal is transmitted through a conventional single mode optical fiber to a remote location. The optical signal received at the remote location is detected with a high speed photodiode, and the transmitted signals are recovered with a conventional RF or microwave receiver. The RF or microwave carriers can be modulated by either analog or digital signals and can be used to carry voice, data, video, digital audio and high definition video, in almost any combination of services.

Transmission of 60 frequency modulated video channels over 18 kilometers of optical fiber is described by R. Olshansky et al in "60-Channel EM Video Subcarrier Multiplexed Optical Communication System", Electronics Letters, Vol. 23, No. 22, pages 1196-1198, October 1987. A coherent subcarrier multiplexed optical communication system is disclosed in U.S. Patent No. 4,989,200 issued January 29, 1991. In the disclosed coherent SCM system, M information channels can be transmitted on an optical carrier by using M subcarriers, each individually modulated with a separate information signal. By combining the above techniques, M information channels can be carried on each of N optical carriers for a total of M x N information channels.

A drawback of an SCM system with multiple optical carriers is that each modulated optical carrier has upper and lower sidebands and also contains second order intermodulation products which fall outside the upper and lower sidebands. To prevent interference between adjacent optical channels, it is necessary to provide a frequency separation between optical carriers of $3f_{max}$, where $f_{max}$ is the maximum subcarrier frequency used to modulate the optical carrier. In order to maximize the transmission bandwidth, it is desirable to achieve close spacing between optical carriers, while minimizing interference.

Quadrature optical modulation involves modulation of two coherent optical carrier components that are 90° apart in phase by separate modulating signals. In quadrature phase sift keying, the modulating signals are digital. Quadrature modulation can be used to simultaneously transmit two independent information signals with a single optical carrier frequency.

According to the present invention, these and other objects and advantages are achieved in a quadrature phase shift keyed optical modulator comprising first modulation means for phase modulating lightwaves in response to a first modulation signal $v_1(t)$, second modulation means for phase modulating lightwaves in response to a second modulation signal $v_2(t)$, an optical divider for coherently coupling an optical carrier to the first and second modulation means, an optical combiner for coherently combining modulated optical carriers from the first and second modulation means and providing an output optical signal, means for providing the first modulation signal $v_1(t) = v_\pi D(t)$ to the first modulation means, where $v_\pi$ is a voltage required to produce a phase shift of $\pi$ at the optical carrier frequency and $D_1(t)$ is a first digital data

signal of amplitude $\pm\frac{1}{2}$, and means for providing the second modulation signal $v_2(t) = v_\pi D_2(t) + v_{\pi/2}$ to the second modulation means, where $v_2(t)$ is a second digital data signal of amplitude $\pm\frac{1}{2}$, and $V_{\pi/2}$ is a voltage required to produce a phase shift of $\pi/2$ at the optical carrier frequency.

According to another aspect of the invention there is provided a quadrature optical phase modulator comprising first modulation means for phase modulating lightwaves in response to a first modulation signal $v_1(t)$, second modulation means for phase modulating lightwaves in response to a second modulation signal $v_2(t)$, an optical divider for coherently coupling an optical carrier to the first and second modulation means, an optical combiner for coherently combining modulated optical carriers from the first and second modulation means and providing an output optical signal, means for providing the first modulation signal $v_1(t)$ to the first modulation means, where $v_1(t)$ is of the form

$$v_1(t) = \Sigma\, \beta_{i1} \cos(\omega_{i1} t + \delta_{i1})$$

and means for providing the second modulation signal $v_2(t)$ to the second modulation means, where $v_2(t)$ is of the form

$$v_2(t) = \Sigma\, \beta_{i2} \cos(\omega_{i2} t + \delta_{i2}) + v_{\pi/2}$$

where

| | |
|---|---|
| $\beta_{i1}, \beta_{i2}$ | = amplitude of the ith subcarrier, |
| $\omega_{i1}, \omega_{i2}$ | = frequency of the ith subcarrier, |
| $\delta_{i1}, \delta_{i2}$ | = phase of the ith subcarrier, and |
| $v_{\pi/2}$ | = voltage required to produce a phase shift of $\pi/2$ at the optical carrier frequency. |

The information signals can be contained in time-varying amplitudes $\beta_{i1}$, $\beta_{i2}$, time-varying sequences $\omega_{i1}$, $\omega_{i2}$ or time-varying phases $\delta_{i1}$, $\delta_{i2}$ of each subcarrier.

According to a further aspect of the invention there is provided a quadrature optical phase modulator comprising first modulation means for phase modulating lightwaves in response to a first modulation signal $v_1(t) + V_\pi$, second modulation means for phase modulating lightwaves in response to a second modulation signal $-v_1(t)$, third modulation means for phase modulating lightwaves in response to a third modulation signal $v_2(t) + v_{\pi/2}$, fourth modulation means for phase modulating lightwaves in response to a fourth modulation signal $-v_2(t) - v_{\pi/2}$, optical divider means for coherently coupling an optical carrier to the first, second, third and fourth modulation means, optical combiner means for coherently combining modulated optical carriers from the first, second, third and fourth modulation means and providing an output optical signal, and means for providing the first, second, third and fourth modulation signals to the first, second, third and fourth modulation means, respectively, where

$$v_1(t) = \Sigma\, \beta_{i1} \cos(\omega_{i1} t + \delta_{i1})$$

$$v_2(t) = \Sigma\, \beta_{i2} \cos(\omega_{i2} t + \delta_{i2})$$

| | |
|---|---|
| $\beta_{i1}, \beta_{i2}$ | = amplitude of the ith subcarrier, |
| $\omega_{i1}, \omega_{i2}$ | = frequency of the ith subcarrier, |
| $\delta_{i1}, \delta_{i2}$ | = phase of the ith subcarrier, and |
| $v_\pi$ | = voltage required to produce a phase shift of $\pi$ at the optical carrier frequency, and |
| $v_{\pi/2}$ | = voltage required to produce a phase shift of $\pi/2$ at the optical carrier frequency. |

In the above optical phase modulators, each modulation means preferably comprises an optical waveguide formed in a substrate and an electrode positioned for phase modulating lightwaves carried in the optical waveguide in response to a modulation signal applied to the electrode. The electrodes can comprise lumped-element electrodes or traveling wave electrodes.

Some embodiments of the invention will now be described, by way of example, with reference to the accompanying drawings in which:

| | |
|---|---|
| FIG. 1 | is a spectral diagram of an optical carrier that is modulated with multiple subcarriers; |
| FIG. 2 | is a spectral diagram which shows the minimum spacing between optical carriers that are modulated with multiple subcarriers in accordance with the prior art; |
| FIG. 3 | is a block diagram of an optical transmitter in accordance with the invention, wherein second order intermodulation products are cancelled; |
| FIG. 4 | is a block diagram of an electrical transmitter used in the optical transmitter of FIG. 3; |
| FIG. 5 | is a schematic diagram of a lumped-element intermod-cancelling optical phase modulator that can be used in the optical transmitter of FIG. 3; |
| FIG. 5A | is a schematic diagram of a traveling wave intermod-cancelling optical phase modulator that can be used in the optical transmitter of FIG. 3; |
| FIG. 6 | is a partial cross-sectional view of the intermod-cancelling optical phase modulator shown in FIG. 5; |
| FIG. 6A | is a block diagram of the signal conditioner shown in FIGS. 5 and 5A; |

FIG. 7 is a block diagram of a coherent optical receiver suitable for use with the optical transmitter of FIG. 3;

FIG. 8 is a spectral diagram which shows the minimum spacing between optical channels in the optical transmitter of FIG. 3;

FIG. 9 is a block diagram of an optical transmitter in accordance with the invention,wherein one sideband of each optical channel and second order intermodulation products are cancelled;

FIG. 10 is a block diagram of a single sideband optical phase modulator used in the optical transmitter of FIG. 9;

FIG. 11 is a block diagram of an electrical transmitter used in the optical transmitter of FIG.9;

FIG. 12 is a spectral diagram which shows the minimum channel between optical channels in the optical transmitter of FIG. 9;

FIG. 13 is a block diagram of a direct detection optical receiver suitable for receiving phase modulated optical signals as generated by the optical transmitters of FIGS. 3 and 9;

FIG. 14 is a schematic diagram of a single sideband optical intensity modulator in accordance with the invention;

FIG. 15 is a block diagram of a direct detection optical receiver suitable for receiving intensity modulated optical signals as generated by the modulator of FIG. 14;

FIG. 16 is a schematic diagram of a single sideband optical phase modulator wherein second-order intermodulation products are not cancelled;

FIG. 17 is a schematic diagram of a quadrature optical phase modulator;

FIG. 18 is a schematic diagram of a quadrature optical phase modulator wherein second-order intermodulation products are cancelled; and

FIG. 19 is a block diagram of a coherent optical receiver suitable for receiving an optical signal including quadrature optical phase modulation with two independent subcarrier multiplexed signals.

A spectral diagram of a subcarrier multiplexed (SCM) system is shown in FIG. 1. Spectral intensity is plotted as a function of frequency. An optical carrier at a frequency $f_{01}$ is modulated with multiple subcarriers. The modulation voltage v(t) is given by

$$v(t) = \Sigma \beta_i \cos (\omega_i t + \delta_i \quad (1)$$

where $\beta_i$ = amplitude of the ith subcarrier, $\omega_i$ = frequency of the ith subcarrier, and $\delta_i$ = phase of the ith subcarrier. The information signal can be contained in a time-varying amplitude $\beta_i$, a time-varying frequency $\omega_i$ or a time-varying phase $\delta_i$ of each subcarrier. The spectrum as shown in FIG. 1 includes an upper sideband 10 and a lower sideband 12 equally spaced from the optical carrier. In addition, the spectrum includes four bands containing second order intermodulation products (IMP's). Band 20 includes second order IMP's at frequencies $f_{01}$ $-(f_i + f_j)$; band 22 contains second order IMP's at frequencies $f_{01}$ $-(F_i - f_j)$; band 24 contains second order IMP's at frequencies $f_{01}$ $+(f_i - f_j)$; and band 26 contains second order IMP's at frequencies $f_{01}$ $+(f_i + f_j)$, where $f_i$ and $f_j$ represent different subcarrier frequencies.

As shown in FIG. 1, band 26 extends higher in frequency than upper sideband 10, and band 20 extends lower in frequency than lower sideband 12. As a result, in optical communication systems utilizing two or more subcarrier multiplexed optical carriers, it has heretofore been necessary to space optical carriers as shown in FIG. 2 to avoid interference from second order IMP's. A spectral diagram of a system including two modulated optical carriers is shown in FIG. 2. A first optical channel includes an upper sideband 30 and a lower sideband 32. A second optical channel includes an upper sideband 34 and a lower sideband 36. In order to prevent second order IMP's from the first optical channel from interfering with lower sideband 36, and to prevent second order IMP's from the second optical channel from interfering with upper sideband 30, it is necessary to space upper sideband 30 from lower sideband 36 by a frequency $f_{max}$, where $f_{max}$ is the maximum modulation frequency. Therefore, the minimum spacing between optical carriers is $3f_{max}$. This spacing between optical channels does not provide an efficient utilization of the available spectrum.

A block diagram of an optical transmitter wherein second order IMP's are cancelled is shown in FIG. 3. By cancelling second order IMP's, closer spacing between optical carriers can be utilized as described hereinafter. A first laser 40 directs an optical carrier at a first frequency $f_1$ to an intermod-cancelling (IC) optical phase modulator 42. A second laser 44 directs an optical carrier at a second optical frequency $f_2$ to an IC optical phase modulator 46. An Nth laser 48 directs an optical carrier at an Nth optical frequency $f_N$ to an IC optical phase modulator 50. The number N of lasers and IC modulators in the system depends on the number

of modulated optical carriers to be transmitted. The outputs of modulators 42, 46---50 are connected to an optical fiber 52 for transmission of a composite optical signal to one or more remote locations. An electrical transmitter 54 provides a modulation signal to modulator 42; an electrical transmitter 56 provides a modulation signal to modulator 46; and an electrical transmitter 58 provides a modulation signal to modulator 50.

The lasers 40, 44---48 can, for example, be distributed feedback semiconductor lasers as described by H. Soda et al. in "Stability in Single Longitudinal Mode Operation in GaInAsP/InP Phase-Adjusted DFB Lasers", IEEE J. Quantum Electronics, Vol. QE-23, June 1987, pages 804-814. A laser control 60 provides to the lasers 40, 44---48 signals which control the optical frequencies of each laser so as to permit close optical carrier frequency spacing.

A block diagram of an electrical transmitter representative of transmitters 54, 56---58 is shown in FIG. 4. A first information carrying signal $S_1$ modulates a voltage controlled oscillator (VCO) 70. A second information carrying signal $S_2$ modulates a VCO 72 and an Nth information carrying signal $S_N$ modulates a VCO 74. The signals $S_1$, $S_2$---$S_N$ can be any signal to be transmitted, such as a digital signal, a voice signal, an audio signal or a video signal. The signals $S_i$, $S_2$---$S_N$ produce frequency modulation of the subcarriers generated by the VCO's 70, 72---74. The VCO's 70, 72---74 have different frequencies in the electrical frequency spectrum, typically in the range from about 0 to 20 GHz. The maximum modulation frequency $f_{max}$ is determined by the 3dB bandwidth of the IC optical phase modulators. The outputs of VCO's 70, 72---74 are connected to the inputs of an electrical power combiner 76. The output of combiner 76, which has the form of the modulation signal of equation (1), is connected to the modulation input of one of the modulators 42, 46---50 shown in FIG. 3. The electrical transmitter utilized in the optical transmitter of FIG. 3 can have different configurations within the scope of the present invention. For example, the VCO's shown in FIG. 4 can be replaced with fixed frequency oscillators and modulators which receive the information carrying signals. This configuration produces phase modulation of the subcarriers.

The details of an optical phase modulator representative of modulators 42, 46---50 are shown in FIGS. 5 and 6. Since the optical modulator shown in FIG. 5 cancels second-order intermodulation products, it is referred to herein as an "intermod-cancelling" optical phase modulator. The modulator of the present invention is a variation of a Mach-Zehnder modulator, or Y-branch interferometric modulator, as disclosed by Alferness in "Guided-Wave Devices for Optical Communication", IEEE Journal of Quantum Electronics, Vol. QE-17, No. 6, June 1981, pages 946-959. The modulator includes an optical waveguide 80 formed on a substrate 82. Typically, the substrate 82 is lithium niobate, and the waveguide 80 is titanium. However, other substrate and waveguide materials are included within the scope of the present invention. The optical waveguide 80 includes an input section 84, an optical divider 86, a first modulation section 88, a second modulation section 90, an optical combiner 92 and an output section 94. The optical divider 86 divides the optical carrier received on input section 84 and coherently couples approximately 50% of the optical carrier power to one end of each of the modulation sections 88 and 90. The other ends of the modulation sections 88 and 90 are connected to the optical combiner 92. The optical combiner 92 coherently combines the optical signals from modulation sections 88 and 90 in equal proportions and provides an output optical signal on output section 94.

The modulation sections 88 and 90 are typically elongated, parallel, spaced-apart waveguide sections. An electrode 96 is positioned along one side of modulation section 88, and an electrode 100 is positioned along one side of modulation section 90. A common electrode 98 is positioned along the other side of each of modulation sections 88 and 90. As shown in FIG. 6, the electrodes 96, 98 and 100 can be metallizations on the surface of substrate 82.

The common electrode 98 is typically connected to ground, and modulation signal voltages are applied to electrodes 96 and 100. A modulation voltage applied between electrode 96 and electrode 98 produces an electric field in optical waveguide modulation section 88. A modulation voltage applied between electrode 100 and electrode 98 produces an electric field in optical waveguide modulation section 90. The electric fields in turn modulate the refractive indices of the optical waveguide modulation sections 88 and 90 and phase modulate the lightwaves carried therein.

The optical phase modulator shown in FIG. 5 utilizes lumped-element electrodes 96 and 100. The bandwidth of lumped-element modulators is limited to several GHz, while traveling wave modulators can have bandwidths of 10-40 GHz. An intermod-cancelling optical phase modulator with traveling wave electrodes is shown in FIG. 5A. Corresponding elements in FIGS. 5 and 5A have the same reference numerals. A traveling wave electrode 104 is positioned along one side of modulation section 88, and a traveling wave electrode 105 is positioned along one side of modulation section 90. The electrodes 104 and 105 each have a 50 ohm termination 106. The electrodes 104 and

105 are designed as transmission lines matched to the input cable, and the modulation signals $v_1(t)$ and $v_2(t)$ are fed colinearly with the propagating optical waves. Traveling wave optical phase modulators are described in the aforementioned Alferness paper.

The modulation signal v(t) as given by equation (1) and generated by the RF transmitter shown in FIG. 4 is applied to a signal conditioner 102. The signal conditioner 102 generates a first signal $v_1(t)$ which is applied to electrode 96 (FIG. 5) or electrode 104 (FIG. 5A) and a second signal $v_2(t)$ which is applied to electrode 100 (FIG. 5) or electrode 105 (FIG. 5A). The modulation signals $v_1(t)$ and $v_2(t)$ are given as follows:

$$v_1(t) = \Sigma\ \beta_i \cos(\omega_i t + \delta_i) + v_\pi \qquad (2)$$

$$v_2(t) = -\Sigma\ \beta_i \cos(\omega_i t + \delta_i) \qquad (3)$$

inverter 108 on the branch that supplies $v_2(t)$ and an adder 109 for adding a DC bias of $v_\pi$ on the branch that supplies $v_1(t)$, as shown in FIG. 6A.

The optical carrier applied to input section 84 is given by:

$$E(t) = E_0 \cos(\omega_0 t) \qquad (4)$$

where $E_0$ = amplitude of the optical carrier and $\omega_0$ = frequency of the optical carrier. The optical signal on output section 94 after modulation of the optical carrier by modulation signals $v_1$ and $v_2$ is given by:

$$e(t) = \sqrt{2}\ E_0 \sin(\omega_0 t) \sin\phi \qquad (5)$$

where $\phi = \pi\ v(t)/v_\pi$. The optical signal given by equation (5) is free of second order intermodulation products.

A coherent optical receiver suitable for receiving the optical signal transmitted on optical fiber 52 by the optical transmitter shown in FIG. 3 and described above, is shown in FIG. 7. The received signal on optical fiber 52 is connected to one input of an optical fiber coupler 110. The output lightwave of a tunable local oscillator laser 112 is coupled through a polarization controller 113 to another input of fiber coupler 110. The received signal and the output lightwave of local oscillator laser 112 are combined by fiber coupler 110, and the combined signal is applied to a wideband photodetector 114, which can be a PIN photodiode. The output of photodetector 114 is coupled through a low noise amplifier 115 to the input of an electrical receiver 116. The local oscillator laser 112 is tunable over a prescribed frequency range. The output of photodetector 114 is an intermediate frequency equal to the difference between the carrier frequency of the received optical signal and the frequency of the lightwave generated by local oscillator laser 112.

The output of amplifier 115 is coupled to the input of polarization control electronics 117, which provides a control signal to polarization controller 113. The polarization controller 113 and the polarization control electronics 117 constitute a control loop which insures that the received optical signal and the lightwave generated by local oscillator laser 112 have the same polarization. polarization control is described by T. Okoski in Journal of Lightwave Technology, Vol. LT-35, page 1232 (1985). The output of amplifier 115 is also coupled to the input of frequency control electronics 118, which provides a frequency control signal to local oscillator laser 112. The frequency control electronics 118 maintains a selected difference, equal to the intermediate frequency, between the optical carrier frequency and the lightwave generated by local oscillator laser 112 to eliminate the effects of drift, temperature variations, and the like.

The coherent optical receiver shown in FIG. 7 and described hereinabove is a heterodyne system in which the frequency of the local oscillator laser is different from the frequency of the optical carrier. In an alternative embodiment, the coherent optical receiver is configured as a homodyne system in which the optical carrier and the local oscillator have the identical frequency and phase, and the intermediate frequency is zero. In a homodyne system, it is necessary to synchronize the phases of the local oscillator and the optical carrier. Phase locking can be achieved using known phase-locked loop techniques. Further details regarding a coherent subcarrier multiplexed optical communication receiver are disclosed in U. S. Patent No. 4,989,200 issued January 29, 1991.

In operation, the frequency of the local oscillator 112 laser is tuned to select a desired optical carrier. The intermediate frequency output of photodetector 114 is processed by receiver 116 to select a desired channel from the SCM channels carried on the optical carrier. The spectral spacing that can be achieved with the optical transmitter of in FIG. 3 is illustrated in FIG. 8. A first optical channel includes a lower sideband 120 and an upper sideband 122. A second optical channel includes a lower sideband 124 and an upper sideband 126. The optical carriers are represented by frequencies $f_{01}$ and $f_{02}$. The second order IMP's have been cancelled using the intermod-cancelling optical phase modulator shown in FIG. 5 or 5A and described above. Thus, adjacent optical channels can be spaced such that the upper sideband 122 of the first optical channel abuts the lower sideband 124 of the second optical channel. This is achieved by a spacing between optical carriers of $2f_{max}$,

where $f_{max}$ is the maximum modulation frequency. In practice, it is desirable to provide a slightly greater channel spacing than $2f_{max}$ to allow for nonideal filter characteristics. Nonetheless, the optical transmitter shown in FIGS. 3-6 and described above permits the channel spacing on the order of $2f_{max}$, whereas prior systems required a channel spacing of at least $3f_{max}$.

An optical transmitter which permits a further reduction in optical channel spacing is shown in FIG. 9. A first laser 130 supplies an optical carrier at a first optical frequency $f_1$ to a first single sideband optical phase modulator 132. A second laser 134 supplies an optical carrier at a second optical frequency $f_2$ to a second single sideband optical phase modulator 136. An Nth laser 138 supplies an optical carrier at an Nth optical frequency $f_N$ to an Nth single sideband optical phase modulator 140. The outputs of modulators 132, 136---140 are connected to an optical fiber 142 which transmits the output of the optical transmitter to one or more remote locations. The modulator 132 receives modulation signals vs and vc from an electrical transmitter 144; the modulator 136 receives modulation signals vs and vc from an electrical transmitter 146; and the modulator 140 receives modulation signals $v_s$ and $v_c$ from an electrical transmitter 148. A laser frequency control 150 supplies control signals to lasers 130, 134---138 for controlling the optical carrier frequencies generated by each of the lasers. The optical transmitter of FIG. 9 includes a laser, a single sideband modulator and an electrical transmitter for each optical carrier. Any desired number N of modulated optical carriers can be transmitted.

A block diagram of a single sideband optical phase modulator representative of the modulators 132, 136---140 is shown in FIG. 10. An input optical waveguide 160 is connected through a an optical divider 162 which coherently couples 50% of an input optical carrier to each of its outputs. One output of optical divider 162 is connected to the input of an intermod-cancelling optical phase modulator 164. The other output of optical divider 162 is connected to the input of an intermod-cancelling optical phase modulator 166. The outputs of intermod-cancelling modulators 164 and 166 are connected by optical waveguides to the respective inputs of an optical combiner 168 which coherently combines the input signals in equal proportions. The optical combiner 168 is connected to an output optical waveguide 170. The intermod-cancelling modulator 164 receives a modulation signal $v_s$, and the intermod-cancelling modulator 166 receives a modulation signal $v_c$. The intermod-cancelling optical phase modulators 164 and 166 are fabricated as shown in FIG. 5 or 5A and described above. That is, each intermod-cancelling modulator 164 and 166 includes a Mach-Zehnder type structure with electrodes 96, 98, 100 (FIG. 5) or electrodes 104, 105, 98 (FIG. 5A) and a signal conditioner 102 (FIG. 6A) for providing modulation signals to the electrodes. In a first embodiment of the invention, the intermod-cancelling modulators 164 and 166 are fabricated on separate substrates, and the interconnecting waveguides comprise optical fibers. The optical divider 162 and the optical combiner 168 comprise optical fiber couplers. In a second embodiment, the intermod-cancelling modulators 164 and 166 are fabricated on a single substrate, and the interconnecting waveguides are fabricated on the same substrate. Thus, for example, optical waveguides 160 and 167, optical divider 162 and optical combiner 168 can comprise titanium regions formed in a lithium niobate substrate.

A modulation voltage vs(t) applied to modulator 164 is given as follows:

$$v_s(t) = \Sigma\, \beta_i \sin(\omega_i t + \delta_i) \quad (6)\ v_s(t) = \Sigma\, \beta_i \sin(\omega_i t + \delta_i) \quad (6)$$

A modulation voltage $v_c(t)$ applied to modulator 166 is given as follows:

$$v_c(t) = \Sigma\, \beta_i \cos(\omega_i t + \delta_i) - v_{\pi/2} \quad (7)$$

where $v_{\pi/2}$ = a voltage which produces a phase shift of $\pi/2$ at the optical carrier frequency. The optical signal output $E_1(t)$ of modulator 164 is given by:

$$E_1(t) = E_0 \sin(\omega_0 t) \sin\{\Sigma\, \beta_i \sin(\omega_i t + \delta_i)\} \quad (8)$$

The optical output signal $E_2(t)$ of modulator 166 is given by:

$$E_2(t) = -E_0 \cos(\omega_0 t) \sin\{\Sigma\, \beta_i \cos(\omega_i t + \delta_i)\} \quad - (9)$$

The outputs of modulators 164 and 166 as given by equations (8) and (9), respectively, are added coherently in optical combiner 168 to give, to the lowest order in 8, the output optical signal $E_3(t)$ of the single sideband optical phase modulator:

$$E_3(t) = -E_0 \cos(w_0 t) \sin\{\Sigma\, \beta_i \cos(\omega_i t + \delta_i)\} - \sin(\omega_0 t) \sin(\omega_i t + \delta_i) \quad (10)$$

The expression given by equation (10) can be reduced to:

$$E_3(t) = E_0 \Sigma\, \beta_i \cos(\omega_0 t + \omega_i t + \delta_i) + 0(\beta^3) \quad - (11)$$

where $0(\beta^3)$ represents third-order intermodulation

products. In the output of the single sideband phase modulator as given by equation (11), the lower sideband and the second order IMP's are cancelled.

A block diagram of an electrical transmitter representative of transmitters 144, 146---148 of FIG. 9 is shown in FIG. 11. A source 180 provides a subcarrier at a frequency $f_1$ to a first electrical modulator 182. An Nth source 184 provides a subcarrier at a frequency $f_N$ to an Nth electrical modulator 186. The modulators 182---186 receive information-carrying signals $S_1$---$S_N$, which may be digital or analog. The outputs of modulators 182---186 are connected to 90° couplers 188---190, respectively. An output 192 of coupler 188 and an output 194 of coupler 190 are connected to the inputs of a power combiner 196. The output $v_s(t)$ of combiner 196, as given by equation (6), is connected to one input of the corresponding single sideband phase modulator in the transmitter of FIG. 9. The inputs to combiner 196 on lines 192 and 194 are given by:

$$v_{si}(t) = \beta_i \sin(\omega_i t + \delta_i) \qquad (12)$$

An output 200 of coupler 188 and an output 202 of coupler 190 are connected to the inputs of a power combiner 204. The output $v_c(t)$ of combiner 204, as given by equation (7), is connected to the other input of the corresponding single sideband phase modulator in the optical transmitter of FIG. 9. The inputs to combiner 204 on lines 200 and 202 are given by:

$$v_{ci}(t) = \beta_i \cos(\omega_i t + \delta_i) \qquad (13)$$

While two electrical channels are illustrated in FIG. 11, it will be understood that the transmitter can have any desired number N of channels within the available bandwidth of the single sideband phase modulator.

The spacing of optical channels that can be achieved in the optical transmitter of FIG. 9 is illustrated in FIG. 12. A first optical channel has an upper sideband 220, a second optical channel has an upper sideband 222, and a third optical channel has an upper sideband 224. The corresponding optical carriers are indicated at $f_{01}$, $f_{02}$, and $f_{03}$, respectively. Since the lower sideband and the second order IMP's have been cancelled in each optical channel, the optical carriers can be spaced as close as $f_{max}$. In practice, a slightly greater spacing than $f_{max}$ is utilized to allow for nonideal filter characteristics. However, the optical transmitter of FIG. 9 provides very high spectral efficiency in SCM optical communication systems utilizing multiple optical carriers.

In the optical transmitter of FIG. 9, the lasers 130, 134---138 can each be a distributed feedback semiconductor laser, a diode-pumped YAG laser, an external cavity semiconductor laser or any other type of coherent optical signal source.

In the single sideband phase modulator illustrated in FIG. 10, the optical divider 162 for dividing the optical beam can be a polarization preserving 3dB splitter such as a planar waveguide splitter or a biconic fiber coupler made to preserve polarization. The outputs of the intermod-cancelling modulators 164 and 166 must be coupled together by a polarization preserving coupler in order to match the polarizations of the two beams that are being combined. The optical phase must be controlled to insure that the outputs of modulators 164 and 166 are combined with phases as required by equations (8)-(10). As indicated above, the modulators 164 and 166, the optical divider 162 and the optical combiner 168 can be monolithically integrated on a single substrate.

The optical transmitter of FIG. 9 wherein one of the sidebands and the second order IMP's are cancelled has been described in connection with a subcarrier multiplexed optical system in which the subcarriers are typically in the microwave range. However, the single sideband phase modulator described herein is not limited to microwave modulation of the optical carrier. The single sideband phase modulator can be used for any modulation frequency range, within the 3dB bandwidth of the modulator, which does not include a DC component. Thus, the single sideband modulator can be applied to baseband systems, provided a line coding technique such as Manchester encoding, 5B6B encoding or the like, which eliminates the DC component of the signal spectrum, is utilized. Furthermore, the single sideband phase modulator described above can be used to cancel either the upper sideband or the lower sideband.

A direct detection optical receiver suitable for receiving a single sideband phase modulated optical signal is shown in FIG. 13. The optical signal received on optical fiber 230 passes through a tunable optical filter 232 to a tunable optical discriminator 234. The output of discriminator 234 is connected to a photodetector 236, and the detected signal is connected to an electrical receiver 240. The photodetector 236 corresponds to the photodetector 114 shown in FIG. 7, and the receiver 240 corresponds to receiver 116. The optical filter 232 and the optical discriminator 234 can each be implemented as a tunable Mach-Zehnder as disclosed by N. Takato et al. in "Silica-Based Integrated Optic Mach-Zehnder Multi-Demultiplexer Family With Channel Spacing of 0.01-250 nm", IEEE Journal of Selected Areas of Communication, Vol. 8, pages 1120-1127 (1990) or as a tunable Fabry-Perot filter as disclosed by J. Stone et al. in

"Pigtailed High Finesse Tunable Fiber Fabry-Perot Interferometers With Large, Medium and Small Free Spectral Ranges", Electronics Letters, Vol. 23, pages 781-783 (1987). The optical filter 232 is used to select one of the optical carriers transmitted on fiber 230. The peak of the filter 232 passband is set to the desired optical carrier frequency. The optical discriminator 234 is tuned such that a linearly increasing or decreasing portion of its frequency response corresponds to the desired sideband. The optical discriminator 234 converts a phase modulated optical carrier to an intensity modulated optical carrier.

The single sideband modulator shown in FIG. 10 and described above provides phase modulation of the optical carrier. A single sideband optical intensity modulator is shown in FIG. 14. An input optical waveguide 246 is connected to an optical divider 248 which provides 3dB phase coherent power division. One output of optical divider 248 is connected through an optical waveguide to a single sideband optical phase modulator 250. The output of phase modulator 250 is connected to one input of an optical combiner 252. The other output of optical divider 248 is connected to one end of an optical waveguide section 254. The other end of waveguide section 254 is connected to the other input of optical combiner 252. The optical combiner 252 adds its inputs in a phase coherent manner and provides an output on an optical waveguide 256. The single sideband phase modulator 250 is fabricated as shown in FIG. 10 and described hereinabove. The modulation inputs vs(t) and vc(t) are provided by a transmitter of the type shown in FIG. 11 and described above. The output of the single sideband intensity modulator on optical waveguide 256 is an intensity modulated optical carrier.

A direct detection receiver suitable for receiving multiple intensity modulated optical carriers is shown in FIG. 15. The optical signal received on an optical fiber 260 is connected through a tunable optical filter 262 to a photodetector 264. The detected signal is connected to a an electrical receiver 266. The optical receiver shown in FIG. 15 is similar to the receiver shown in FIG. 13 and described above except that the optical discriminator of FIG. 13 is omitted. The tunable optical filter 262 is used to select one of the optical carriers transmitted on optical fiber 260. The intensity modulated optical carrier selected by filter 262 is detected, and the detected signal is provided to receiver 266.

For some applications, it may not be necessary to cancel second-order intermodulation products. In this case, a single sideband optical phase modulator similar to the intermod-cancelling optical phase modulator shown and described above can be used. A schematic diagram of an intermod-cancelling optical modulator modified for use as a single sideband optical modulator is shown in FIG. 16. The optical modulator shown in FIG. 16 corresponds to the optical modulator of FIG. 5, except that the signal conditioner 102 is omitted, and different modulation signals are applied to the electrodes. A modulation voltage $v_s(t)$ as given by equation (6) is applied to electrode 96, and a modulation voltage $v_c(t)$ as given by equation (7) is applied to electrode 100.

Alternatively, the traveling wave intermod-cancelling optical modulator of FIG. 5A can be modified and utilized in the same manner. The output of the single sideband optical modulator shown in FIG. 16 is given by:

$$E(t) = E_o\{\cos(\omega_o t) \cos (\phi_s + \sin(\omega_o t) \cos (\phi_c) + \Sigma \beta_i \cos (\omega_o t + \omega_i t + \delta_i) + 0(\beta^3)\} \qquad (14)$$

where

$$\phi_s(t) = \pi v_s(t)/v_\pi, \text{ and}$$
$$\phi_c(t) = \pi v_c(t)/v_\pi.$$

The first two terms of equation (14) represent second-order (and other even order) intermodulation products. The third term of equation (14) is the desired upper sideband. Thus, a single sideband optical modulator with second-order IMP's present in the output is shown in FIG. 16. This configuration is useful in situations where second-order IMP's are relatively small.

According to another aspect of the invention, there is provided a quadrature phase shift keyed optical modulator. A schematic diagram of an intermod-cancelling optical phase modulator modified for use as a quadrature phase shift keyed optical modulator is shown in FIG. 17. The optical modulator shown in FIG. 17 corresponds to the optical modulator of FIG. 5, except that the signal conditioner 102 is omitted, and different modulation signals are applied to the electrodes. A modulation voltage $v_1(t)$ is applied to electrode 96, and a modulation voltage $v_2(t)$ is applied to electrode 100. The modulation voltage $v_1(t)$ is given by

$$v_1(t) = v_\pi D_1(t) \qquad (15)$$

and the modulation voltage $v_2(t)$ is given by

$$v_2(t) = v_\pi D_2(t) + v_{\pi/2} \qquad (16)$$

where $D_1(t)$ and $D_2(t)$ are digital data signals of amplitude $\pm\frac{1}{2}$. The digital data signals $D_1(t)$ and $D_2(t)$, which are independent signals, can be generated by any suitable digital signal sources. Alter-

natively, the traveling wave intermod-cancelling optical modulator of FIG. 5A can be modified and utilized in the same manner, with modulation signals $v_1(t)$ and $v_2(t)$ applied to traveling wave electrodes 104 and 105, respectively. The output signal of the optical modulator of FIG. 17 on output waveguide section 94 is given by

$$E(t) - E_o \{\cos [\omega_o + {}_\pi D_1(t)] + \sin [\omega_o t + \pi D_2(t)]\} \quad (17)$$

This represents a quadrature phase shift keyed optical signal.

The receiver shown in FIG. 7 and described hereinabove is suitable for receiving the quadrature phase shift keyed optical signal represented by equation (17). In order to recover the data signal $D_1(t)$, the local oscillator laser 112 supplies a lightwave of the form cos $(\omega_0 t)$ through the polarization controller 113 to the fiber coupler 110. In order to recover the digital data signal $D_2(t)$, the local oscillator laser 112 supplies a lightwave of the form sin $(\omega_0 t)$ through the polarization controller 113 to the fiber coupler 110. The optical modulator shown in FIG. 17 can be used as a quadrature optical phase modulator for subcarrier multiplexed signals. In this case, the modulation signal $v_1(t)$ applied to electrode 96 is given by

$$v_1(t) = \Sigma \beta_{i1} \cos (\omega_{i1} + \delta_{i1}) \quad (18)$$

and the modulation signal $v_2(t)$ applied to electrode 100 is given by

$$v_2(t) = \Sigma \beta_{i2} \cos (\omega_{i2} + \delta_{i2}) + v_{\pi/2} \quad (19)$$

where

$\beta_{i1}, {}_{\beta i2}$ = amplitude of the ith subcarrier,

$\omega_{i1}, \omega_{i2}$ = frequency of the ith subcarrier,

$\delta_{i1}, \delta_{i2}$ = phase of the ith subcarrier, and

$v_\pi$ = voltage required to produce a phase shift of $\pi$ at the optical carrier frequency, and

$v_{\pi/2}$ = voltage required to produce a phase shift of $\pi/2$ at the optical carrier frequency.

The information signals can be contained in time-varying amplitudes $\beta_{i1}$, ${}_{\beta i2}$, time-varying frequencies $\omega_{i1}$, $\omega_{i2}$, or time-varying phases $\delta_{i1}$, $\delta_{i2}$ of each subcarrier. The modulation signals $v_1(t)$ and $v_2(t)$, as given by equations (18) and (19), are totally independent. Each of the modulation signals $v_1(t)$ and $v_2(t)$ can be generated by an electrical transmitter of the type shown in FIG. 4 and described hereinabove. The term $v_{\pi/2}$ in equation (19) is obtained by adding a suitable DC bias voltage to the modulation signal.

The traveling wave intermod-cancelling optical modulator of FIG. 5A can be modified and utilized with two independent subcarrier multiplexed signals in the same manner as the optical modulator of FIG. 17. The modulation signal $v_1(t)$ given by equation (18) is applied to traveling wave electrode 104, and the modulation signal $v_2(t)$ given by equation (19) is applied to traveling wave electrode 105. The output signal from the optical modulator of FIG. 17 for the modulation signals given equations (18) and (19) is given by

$$E_{(t)} = \cdot E_o \{ \cos [\omega_o t + \pi v_1(t)/v_\pi] + \sin [\omega_o t + \pi v_2(t)/v_\pi]\} \quad (20)$$

To the lowest order in $\beta_i$, the output signal of the optical modulator is given by

$$E(t) = E_o \{-\sin (W_o t) \Sigma \beta_{i1} \cos (\omega_{i1} t + \delta_{i1}) + \cos (\omega_o t) \Sigma \beta_{i2} \cos (\omega_{i2} t + \delta_{i2}) + 0(\beta^2)\} \quad (21)$$

where $0(\beta^2)$ represents second-order intermodulation products.

A coherent optical receiver suitable for receiving the optical signal transmitted by the optical modulator of FIG. 17 using the modulation signals of equations (18) and (19) is shown in FIG. 19. The portion of the receiver including optical fiber 52, fiber coupler 110, photodetector 114, amplifier 115, local oscillator laser 112, polarization controller 113, polarization control electronics 117 and frequency control electronics 118 is the same as the corresponding portion of the optical receiver shown in FIG. 7 and described hereinabove. The output of amplifier 115 is connected to one input of an RF or microwave mixer 330. The output of an RF or microwave local oscillator 332 is connected to the other input of mixer 330. The output of mixer 330 is connected to an input of an RF or microwave receiver 334. The output of amplifier 115 is connected to an input of a frequency control unit 336. The output of frequency control unit 336 is connected to local oscillator 332. The frequency control unit 336 provides a control signal which controls the frequency of the local oscillator 332. The received signal, as given by equation (20), is heterodyned with the lightwave from local oscillator laser 112 at a frequency $\omega_{1o}$ where $\omega_{if} = \omega_0 - \omega_{1o}$. The output of photodetector 114 is given by

$$I(t) = 2E_o E_{1o} \{ \cos[\omega_{if} t + \pi v_1(t)/v_\pi] + \sin [\omega_{if} t + \pi v_2(t)/v_\pi] \} \quad (22)$$

To the lowest order in $\beta_i$, equation (22) can be expressed as

$$L(t) = 2E_o E_{1o} \{-\sin (\omega_{if} t \Sigma \beta_{i1} \cos (\omega_{i1} t) + \delta_{i1}) + \cos (\omega_{if} t) \Sigma \beta_{i2} \cos (\omega_{i2} t) + \delta_{i2}) + 0(\beta^2) \} \quad (23)$$

Electronic quadrature phase detection is performed by multiplying the amplified output signal of photodetector 114, as given by equation (22), by sin ($\omega_{if}t$) or cos ($\omega_{if}t$) from local oscillator 332. The modulation signals $v_1(t)$ or $v_2(t)$, as given by equations (18) and (19), respectively, are recovered at the output of mixer 330 and supplied to receiver 334.

A quadrature optical phase modulator which cancels second-order intermodulation products is shown in schematic form in FIG. 18. The quadrature optical phase modulator of FIG. 18 includes a first optical phase modulator 270 and a second optical phase modulator 272, each of which is constructed in the same manner as the optical phase modulator shown in FIG. 5 and described hereinabove (with the signal conditioner 102 omitted). The modulator 270 includes an electrode 274 positioned adjacent to an optical waveguide section 276, an electrode 278 positioned adjacent to an optical waveguide section 280, a common electrode 282 adjacent to waveguide sections 276 and 280, an optical divider 284 for coherently coupling an optical carrier to waveguide sections 276 and 280, and an optical combiner 286 for coherently combining modulated optical carriers from waveguide sections 276 and 280. The optical modulator 272 includes an electrode 290 positioned adjacent to an optical waveguide section 292, an electrode 294 positioned to an optical waveguide section 296, a common electrode 298 adjacent to waveguide sections 292 and 296, an optical divider 300 for coherently coupling an optical carrier to waveguide sections 292 and 296, and an optical combiner for coherently combining modulated optical carriers from waveguide sections 292 and 296. An input optical divider 304 coherently couples an optical carrier to modulators 270 and 272, and an output optical combiner 306 coherently combines modulated optical carriers from modulators 270 and 272. Optional adjustment electrodes 308 and 310 can be positioned adjacent to the output optical waveguide of modulator 272 or 270 for adjusting the phase of the optical signal to insure phase quadrature. Alternatively, the traveling wave intermod-cancelling modulator of FIG. 5A, with signal conditioner 102 omitted, can be utilized in place of each of modulators 270 and 272.

The quadrature optical phase modulator of FIG. 18 is driven by modulation signals which result in cancellation of second-order intermodulation products. The electrode 274 of modulator 270 is driven by a signal $v_1(t) + v_\pi$, and the electrode 278 of modulator 270 is driven by a signal $-v_1(t)$, where $v_1(t)$ is given by equation (18). Electrode 290 of modulator 272 is driven by a signal $v_2(t) + v_{\pi/2}$, and electrode 294 of modulator 272 is driven by a signal $-v_2(t) - v_{\pi/2}$, where $v_2(t)$ is given by equation (19) with the $v_{\pi/2}$ term of equation (19) omitted. The output of the quadrature optical phase modulator of FIG. 18 is given by

$$E(t) = E_o(t) \{ \cos (\omega_o t) \sin \phi_1 + \sin (\omega_o t) \sin \phi_2 ) \quad (24)$$

where $\phi_1 = \pi v_1(t)/v_\pi$, and $\phi_2 = \pi v_2(t)/v_\pi$. The modulation signals applied to electrodes 274, 278, 290 and 294 can be generated by electrical transmitters of the type shown in FIG. 4 and described hereinabove, with appropriate signal inversion and addition of DC bias voltages. An adjustable DC voltage can be applied between electrodes 308 and 310 to insure phase quadrature between the output signals from modulators 270 and 272.

The coherent optical receiver shown in FIG. 19 and described hereinabove can be used for recovering the information signals transmitted by the optical modulator of FIG. 18. The received optical signal on optical fiber 52 is heterodyned with a lightwave from local oscillator laser 112 at a frequency $\omega_{1o}$ where $\omega_{if} = \omega_0 - \omega_{1o}$. The output of photodetector 114 is given by

$$L(t) = 2E_oE_{1o} \{ \cos [\omega_{if}t \sin [\beta_{i1} \cos (\omega_{i1}t + \delta_{i1})] + \sin [\omega_{if}t] \sin [\Sigma\, \beta_{i2} \cos (\omega_{i2}t + \delta_{i2})] \} \quad (25)$$

Electronic quadrature phase detection is performed by heterodyning the amplified output signal of photodetector 114, as given by equation (25), with either sin ($\omega_{if}t$) or cos ($\omega_{if}t$) from local oscillator 332. The modulation signals $v_1(t)$ or $v_2(t)$, as given by equations (18) and (19), respectively, are recovered at the output of mixer 330 and supplied to receiver 334. In the signal given by equation (25), second-order intermodulation products have been cancelled.

While there have been shown and described what are at present considered the preferred embodiments of the present invention, it will be obvious to those skilled in the art that various changes and modifications may be made therein without departing from the scope of the invention as defined by the appended claims.

## Claims

1. A quadrature phase shift keyed optical modulator comprising:

first modulation means for phase modulating lightwaves in response to a first modulation signal $v_1(t)$;

second modulation means for phase modulating lightwaves in response to a second modulation signal $v_2(t)$;

an optical divider for coherently coupling an optical carrier to said first and second mod-

ulation means;

an optical combiner for coherently combining modulated optical carriers from said first and second modulation means and providing an output optical signal;

means for providing said first modulation signal $v_1(t) = v_\pi D_1(t)$ to said first modulation means, where $v_\pi$ is a voltage required to produce phase shift of $\pi$ at the optical carrier frequency and $D_1(t)$ is a first digital data signal; and

means for providing said second modulation signal $v_2(t) = v_\pi D_2(t) + v_{\pi/2}$ to said second modulation means, where $D_2(t)$ is a second digital data signal and $V_{\pi/2}$ is voltage required to produce a phase shift of $\pi/2$ at the optical carrier frequency.

2. An optical modulator as defined in claim 1 wherein said first modulation means and said second modulation means each comprise an optical waveguide and an electrode positioned for phase modulating lightwaves carried in said optical waveguide in response to a modulation signal applied to said electrode.

3. An optical modulator as defined in claim 2 wherein the electrodes of said first and second modulation means comprise lumped-element electrodes.

4. An optical modulator as defined in claim 2 wherein the electrodes of said first and second modulation means comprise traveling wave electrodes.

5. A quadrature optical phase modulator comprising:

first modulation means for phase modulating lightwaves in response to a first modulation signal $v_1(t)$;

second modulation means for phase modulating lightwaves in response to a second modulation signal $v_2(t)$;

an optical divider for coherently coupling an optical carrier to said first and second modulation means;

an optical combiner for coherently combining modulated optical carriers from said first and

second modulation means and providing an output optical signal;

means for providing said first modulation signal $v_1(t)$ to said first modulation means, where $v_1(t)$ is of the form

where

$\beta_{i1}$ = amplitude of the ith subcarrier,

$\omega_{i1}$ = frequency of the ith subcarrier,

$\delta_{i1}$ = phase of the ith subcarrier; and

means for providing said second modulation signal $v_2(t)$ to said second modulation means, where $v_2(t)$ is of the form

$$v_2(t) = \Sigma\beta_{i2}\cos(\omega_{i2}t + \delta_{i2}) + v_{\pi/2},$$

where

$\beta_{i2}$ = amplitude of the ith subcarrier,

$\omega_{i2}$ = frequency of the ith subcarrier,

$\delta_{i2}$ = phase of the ith subcarrier; and

$v_{\pi/2}$ = voltage required to produce a phase shift of $\pi/2$ at the optical carrier frequency.

6. An optical modulator as defined in claim 5 wherein said first modulation means and said second modulation means each comprise an optical waveguide and an electrode positioned for phase modulating lightwaves carried in said optical waveguide in response to a modulation signal applied to said electrode.

7. An optical modulator as defined in claim 6 wherein the electrodes of said first and second modulation means comprise lumped-element electrodes.

8. An optical modulator as defined in claim 6 wherein the electrodes of said first and second modulation means comprise traveling wave electrodes.

9. A quadrature optical phase modulator comprising:

first modulation means for phase modulating lightwaves in response to a first modulation signal $v_1(t) + v_\pi$;

second modulation means for phase modulating lightwaves in response to a second modulation signal $-v_1(t)$;

third modulation means for phase modulating lightwaves in response to a third modulation signal $v_{2(t)+v\pi/2}$;

fourth modulation means for phase modulating lightwaves in response to a fourth modulation signal $-v_{2(t)-v\pi/2}$

optical divider means for coherently coupling an optical carrier to said first, second, third and fourth modulation means;

optical combiner means for coherently combining modulated optical carriers from said first, second, third and fourth modulation means and providing an output optical signal; and

means for providing said first, second, third and fourth modulation signals to said first,

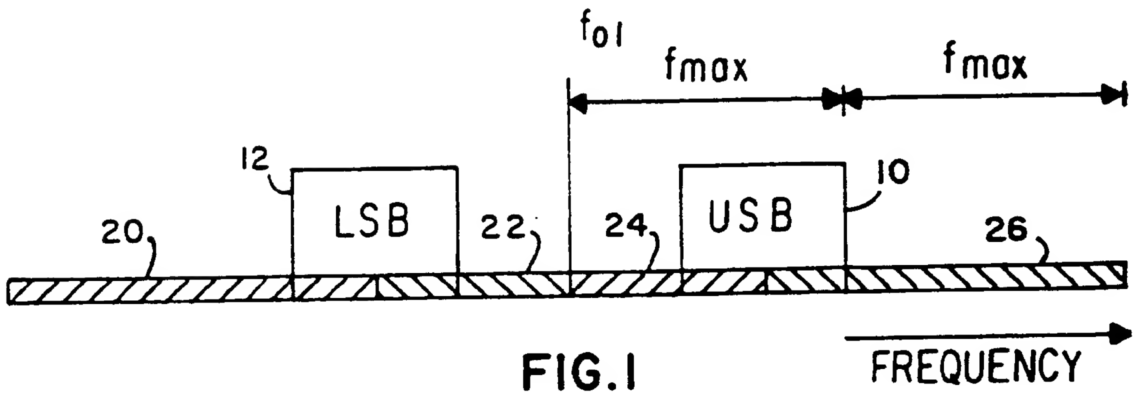
second, third and fourth modulation means, respectively, where

| | |
|---|---|
| $v_1(t)$ | $= \Sigma\ \beta_{i1} \cos(\omega_{i1}t + \delta_{i1})$ |
| $v_2(t)$ | $= \Sigma\ \beta_{i2} \cos(\omega_{i2}t + \delta_{i2})$ |
| $\beta_{i1}, \beta_{i2}$ | = amplitude of the ith subcarrier, |
| $\omega_{i1}, \omega_{i2}$ | = frequency of the ith subcarrier, |
| $\delta_{i1}, \delta_{i2}$ | = phase of the ith subcarrier, and |
| $V_\pi$ | = voltage required to produce a phase shift of $\pi$ at the optical carrier frequency, and |
| $V_{\pi/2}$ | = voltage required to produce a phase shift of $\pi/2$ at the optical carrier frequency. |

**10.** An optical phase modulator as defined in claim 9 wherein said first, second, third and fourth modulation means each comprise an optical waveguide and an electrode positioned for phase modulating lightwaves carried in said optical waveguide in response to a modulation signal applied to said electrode.

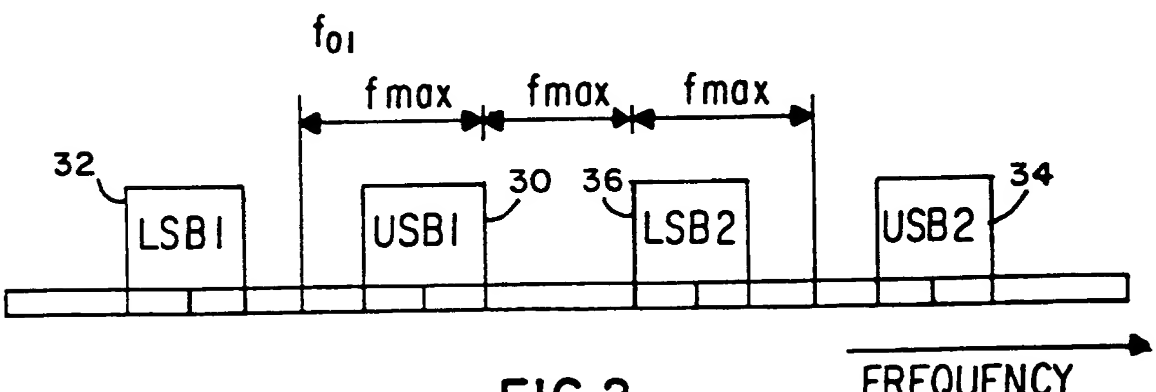
**11.** An optical phase modulator as defined in claim 10 wherein the electrodes of said, first, second, third and fourth modulation means comprise lumped-element electrodes.

**12.** An optical phase modulator as defined claim 10 wherein the electrodes of said first, second, third and fourth modulation means comprise traveling wave electrodes.



$f_{01}$
fmax
fmax
12
LSB
10
USB
20
22
24
26
FREQUENCY


FIG.1



$f_{01}$
fmax
fmax
fmax
32
LSB1
USB1
30
36
LSB2
USB2
34
FREQUENCY


FIG.2

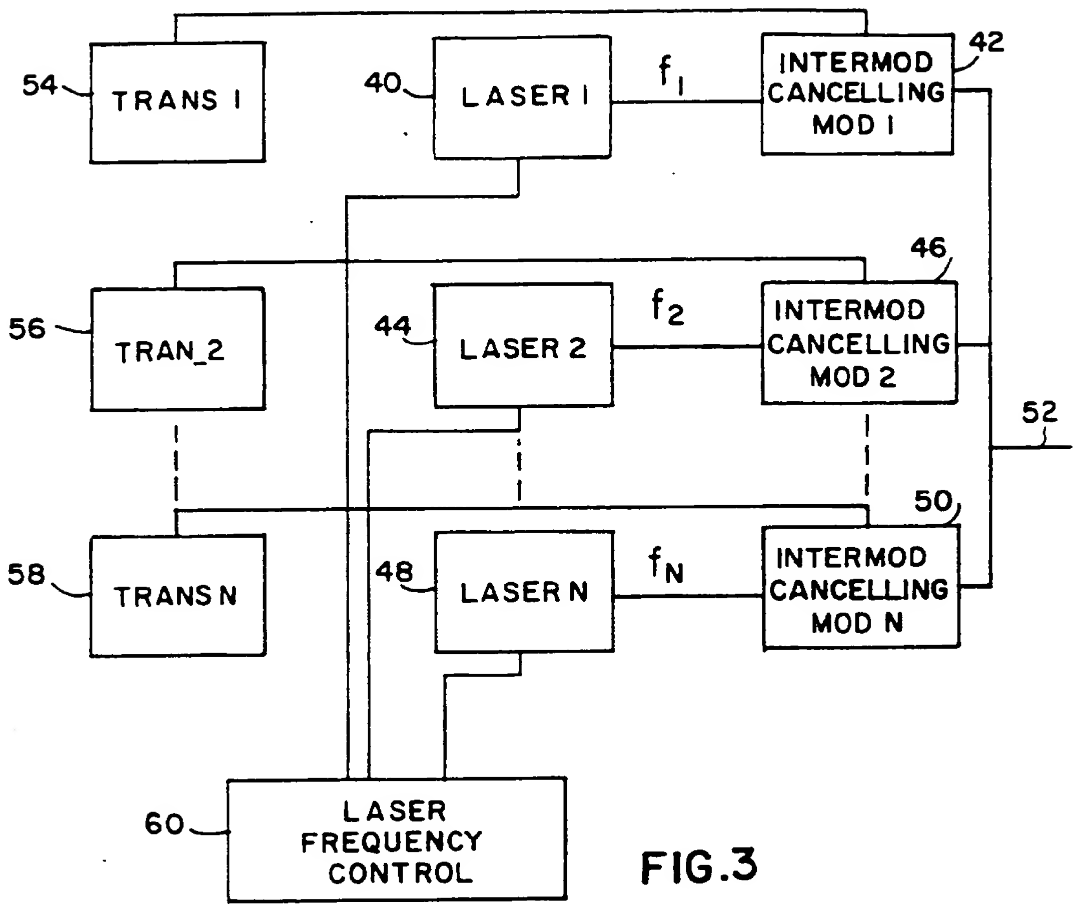

54
TRANS I
40
LASER I
$f_1$
INTERMOD CANCELLING MOD I
42
46
56
TRAN_2
44
LASER 2
$f_2$
INTERMOD CANCELLING MOD 2
52
50
58
TRANS N
48
LASER N
$f_N$
INTERMOD CANCELLING MOD N
60
LASER FREQUENCY CONTROL

FIG.3

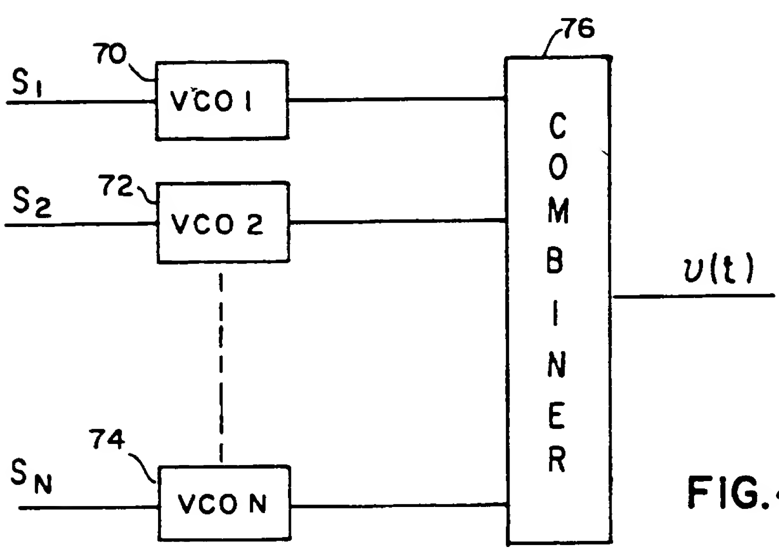

76
$S_1$
70
VCO I
$S_2$
72
VCO 2
COMBINER
$v(t)$
74
$S_N$
VCO N

FIG.4

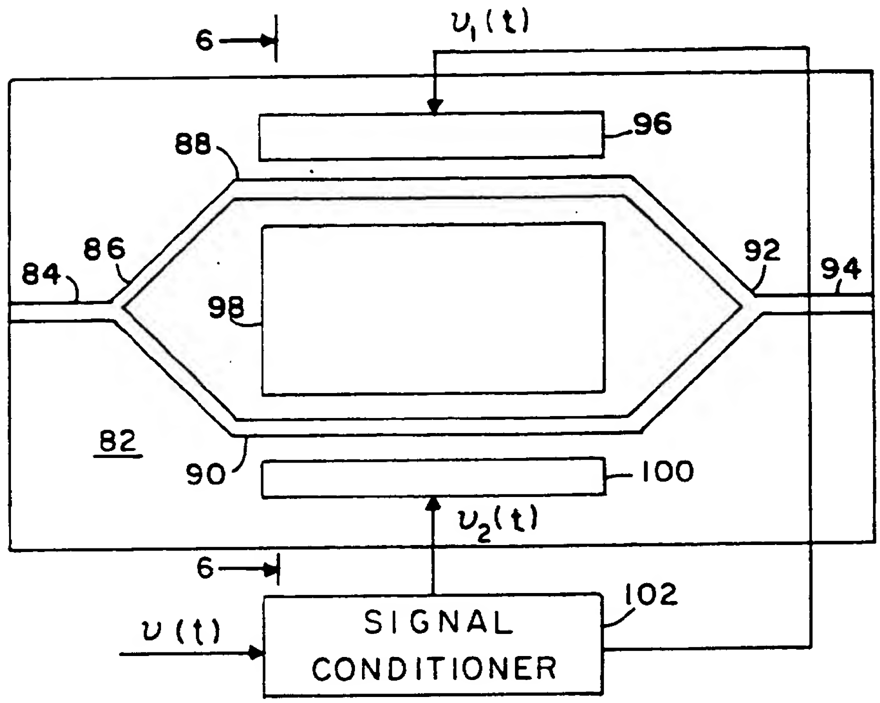

6
$v_1(t)$
96
88
86
84
92
94
98
82
90
100
$v_2(t)$
6
102
$v(t)$
SIGNAL
CONDITIONER

FIG.5

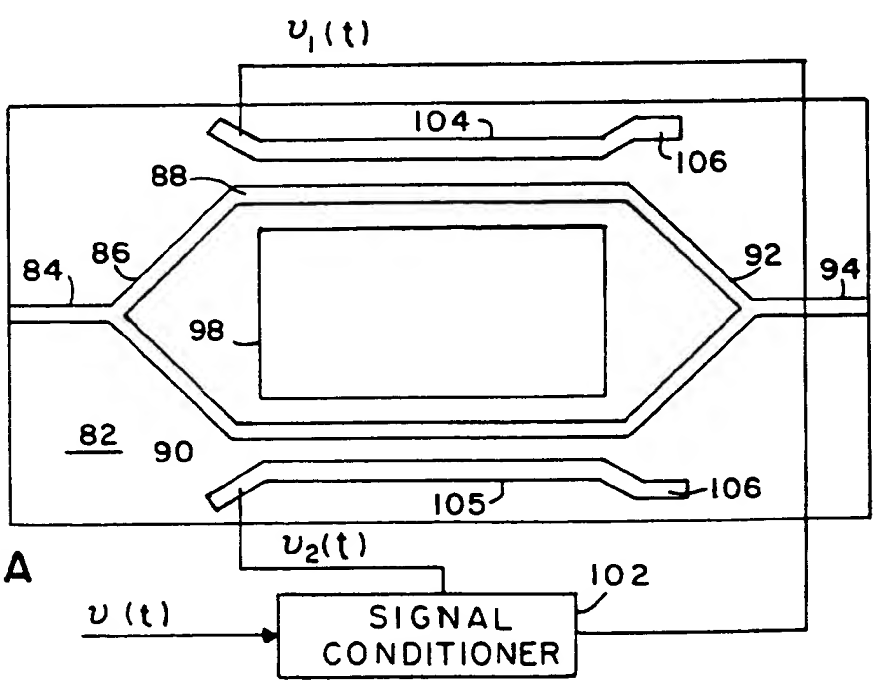

$v_1(t)$
104
106
88
84
86
92
94
98
82
90
105
106
$v_2(t)$
102
$v(t)$
SIGNAL
CONDITIONER

FIG.5A

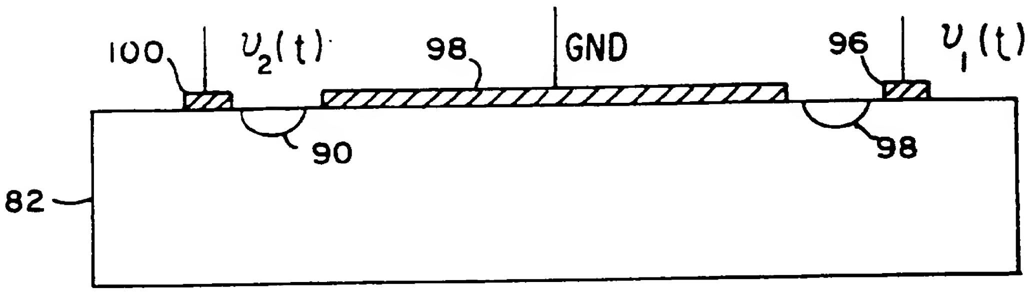

100
$v_2(t)$
98
GND
96
$v_1(t)$
90
98
82

FIG. 6

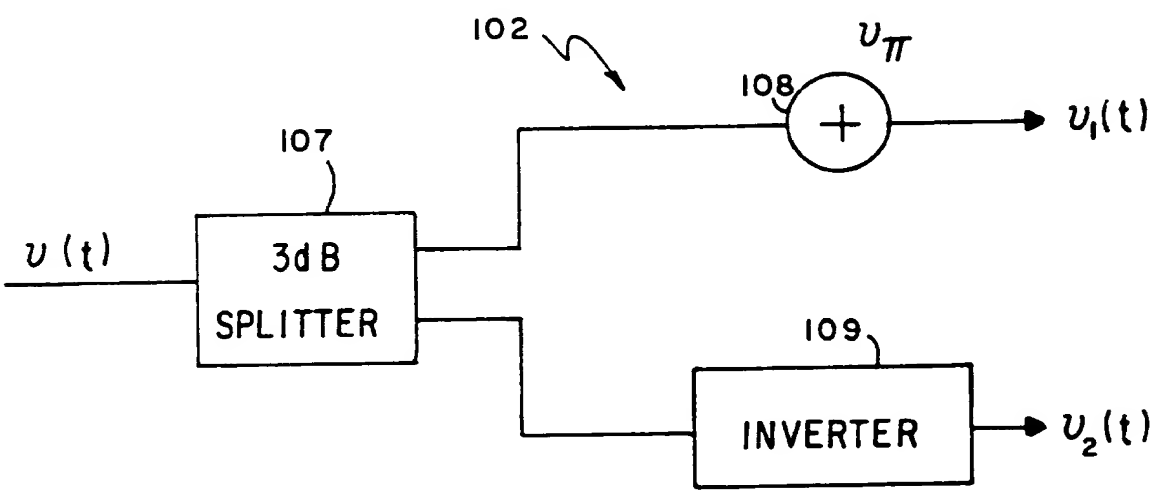

102
$v_\pi$
108
$v_1(t)$
107
$v(t)$
3dB
SPLITTER
109
INVERTER
$v_2(t)$

FIG. 6A

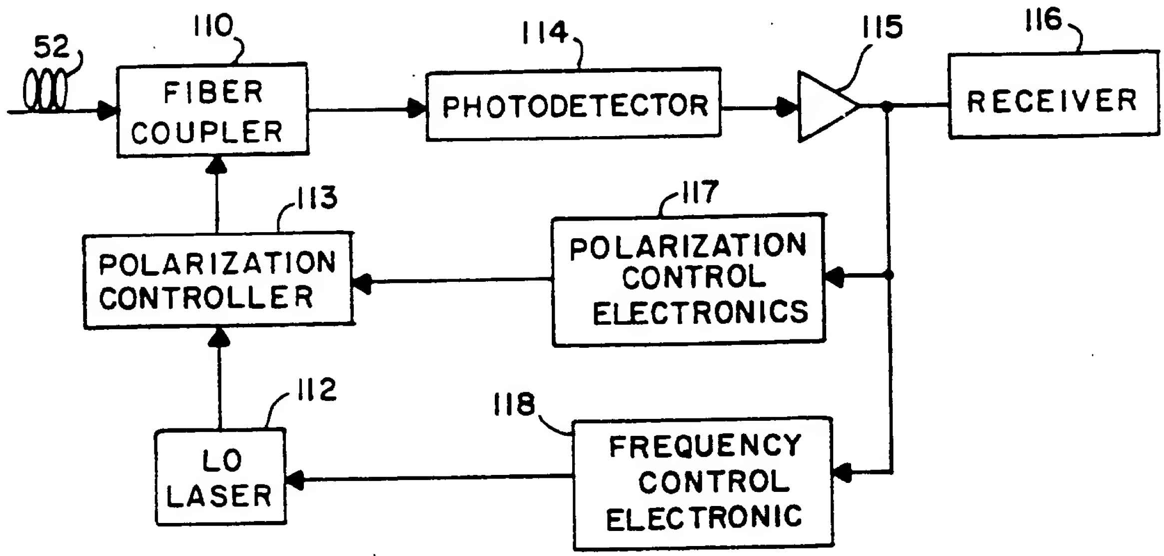

52
110
FIBER COUPLER
114
PHOTODETECTOR
115
116
RECEIVER
113
POLARIZATION CONTROLLER
117
POLARIZATION CONTROL ELECTRONICS
112
LO LASER
118
FREQUENCY CONTROL ELECTRONIC

FIG.7

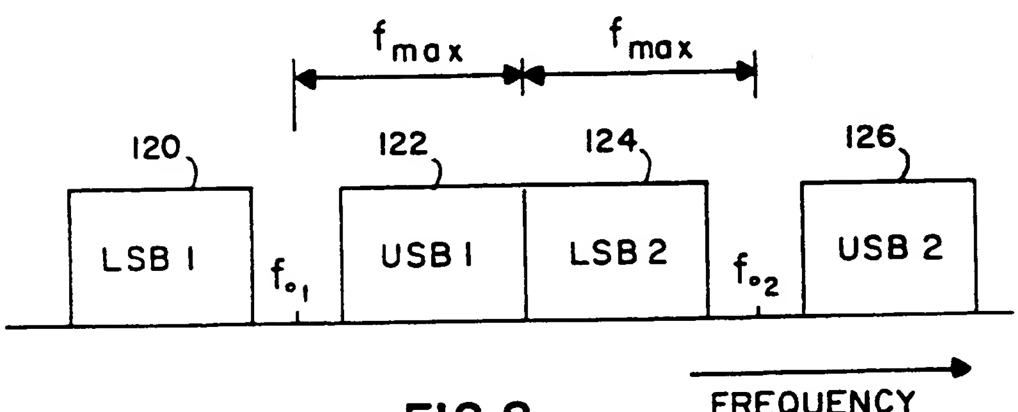

$f_{max}$
$f_{max}$
120
122
124
126
LSB 1
USB 1
LSB 2
USB 2
$f_{o_1}$
$f_{o_2}$
FREQUENCY

FIG.8

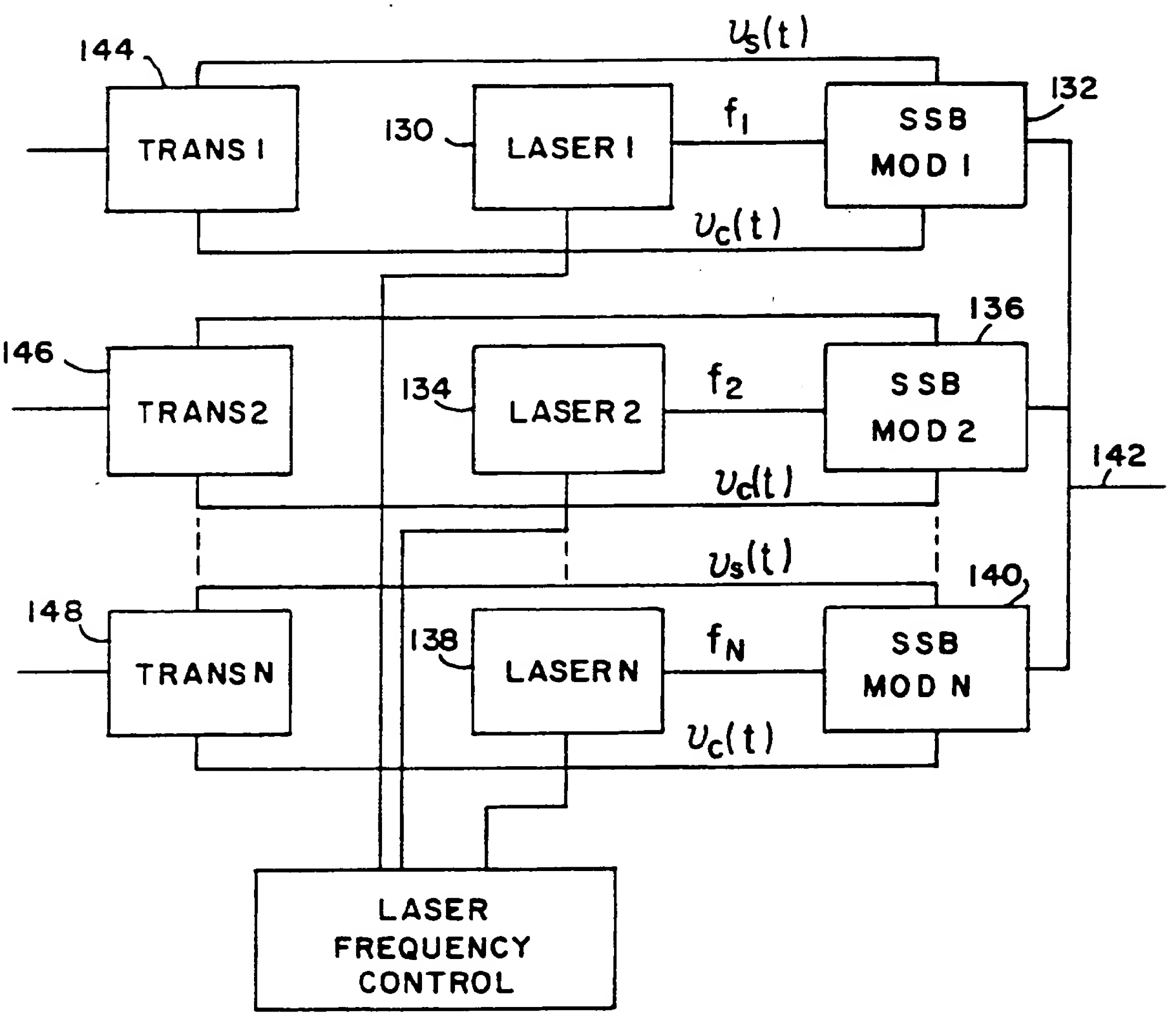
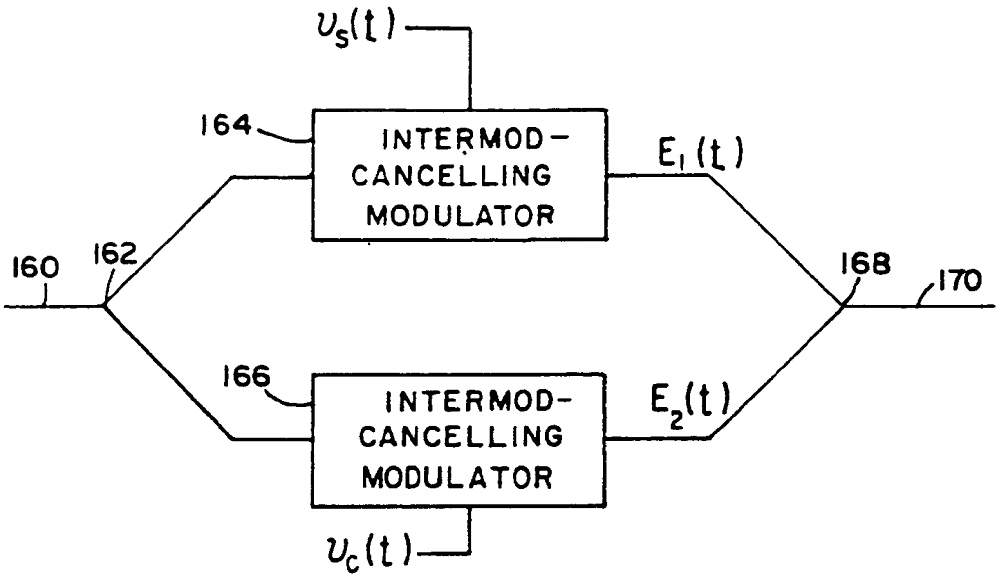
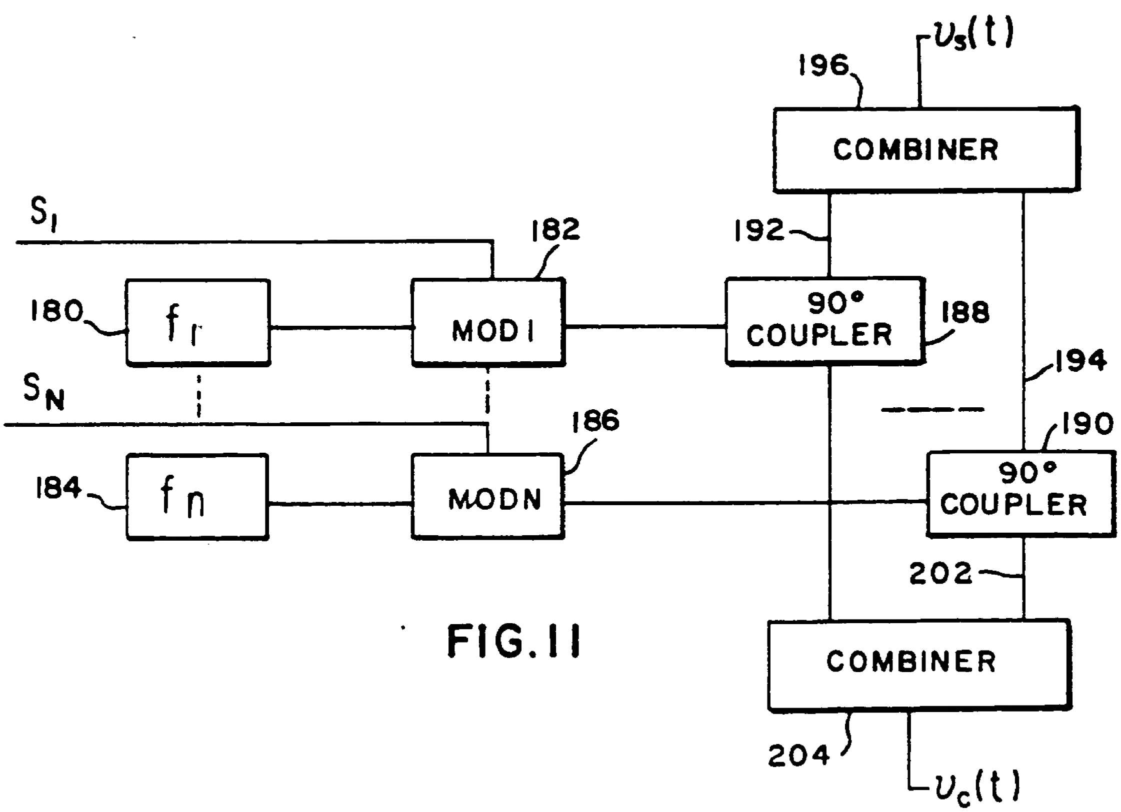

144
TRANS 1
130
LASER 1
$f_1$
SSB
MOD 1
132
$\upsilon_s(t)$
$\upsilon_c(t)$
146
TRANS2
134
LASER 2
$f_2$
SSB
MOD 2
136
$\upsilon_c(t)$
142
$\upsilon_s(t)$
148
TRANS N
138
LASER N
$f_N$
SSB
MOD N
140
$\upsilon_c(t)$
LASER
FREQUENCY
CONTROL

FIG. 9



$v_s(t)$
164
INTERMOD-CANCELLING MODULATOR
$E_1(t)$
160
162
168
170
166
INTERMOD-CANCELLING MODULATOR
$E_2(t)$
$v_c(t)$


FIG.10



$v_s(t)$
196
COMBINER
$S_1$
182
192
180
$f_r$
MOD I
90° COUPLER
188
194
$S_N$
186
190
184
$f_n$
MODN
90° COUPLER
202
COMBINER
204
$v_c(t)$


FIG.11

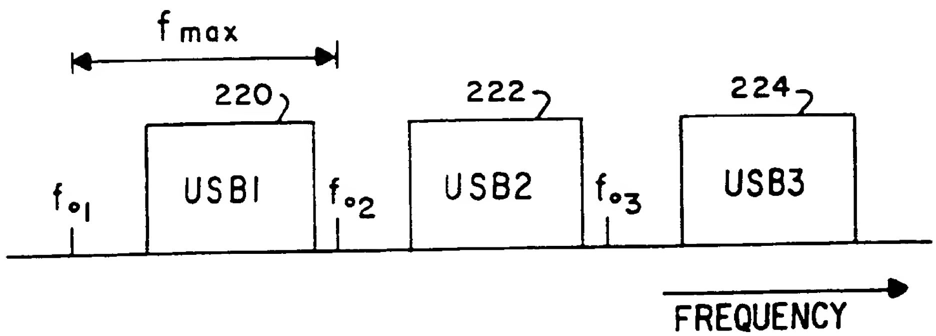

f max
220
222
224
USB1
USB2
USB3
$f_{o1}$
$f_{o2}$
$f_{o3}$
FREQUENCY

FIG.12

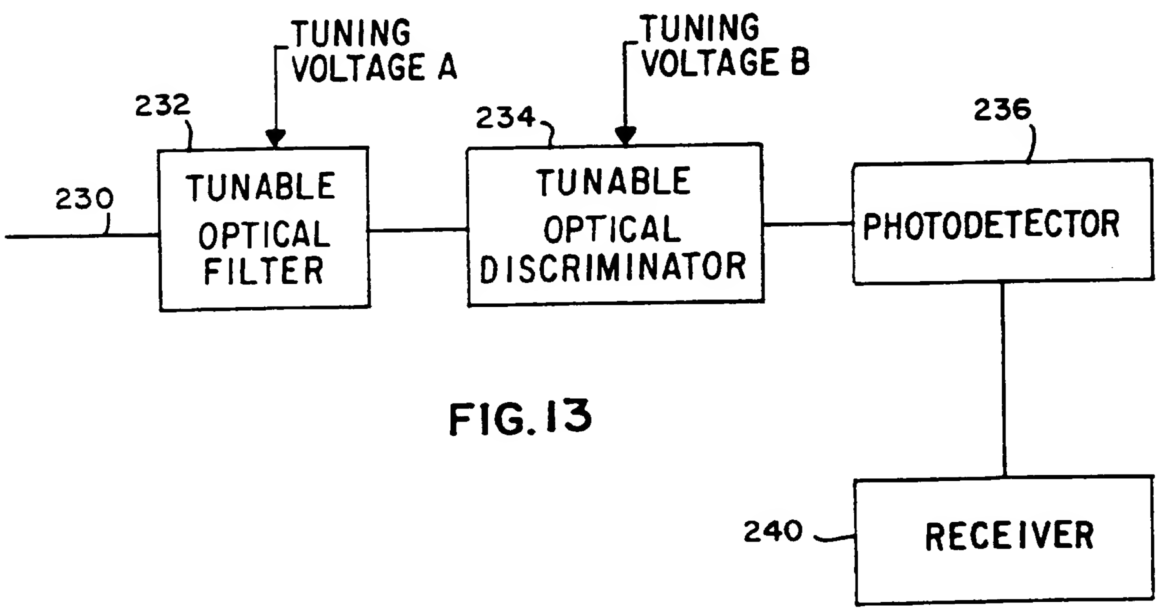

TUNING VOLTAGE A
TUNING VOLTAGE B
232
234
236
230
TUNABLE OPTICAL FILTER
TUNABLE OPTICAL DISCRIMINATOR
PHOTODETECTOR
240
RECEIVER

FIG.13

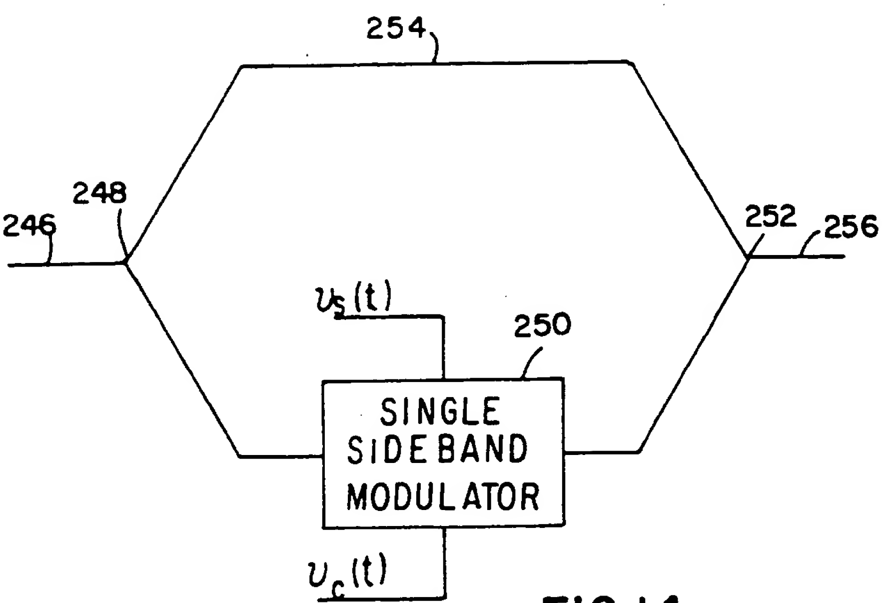

254
248
246
252
256
$v_s(t)$
250
SINGLE SIDEBAND MODULATOR
$v_c(t)$

FIG.14

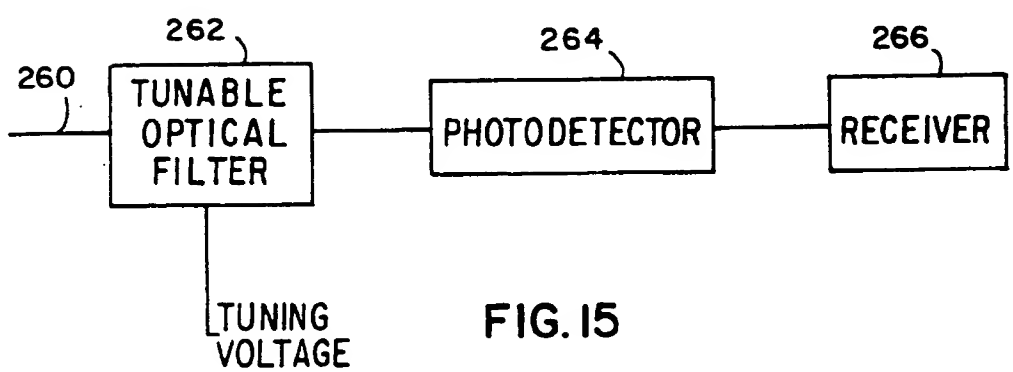
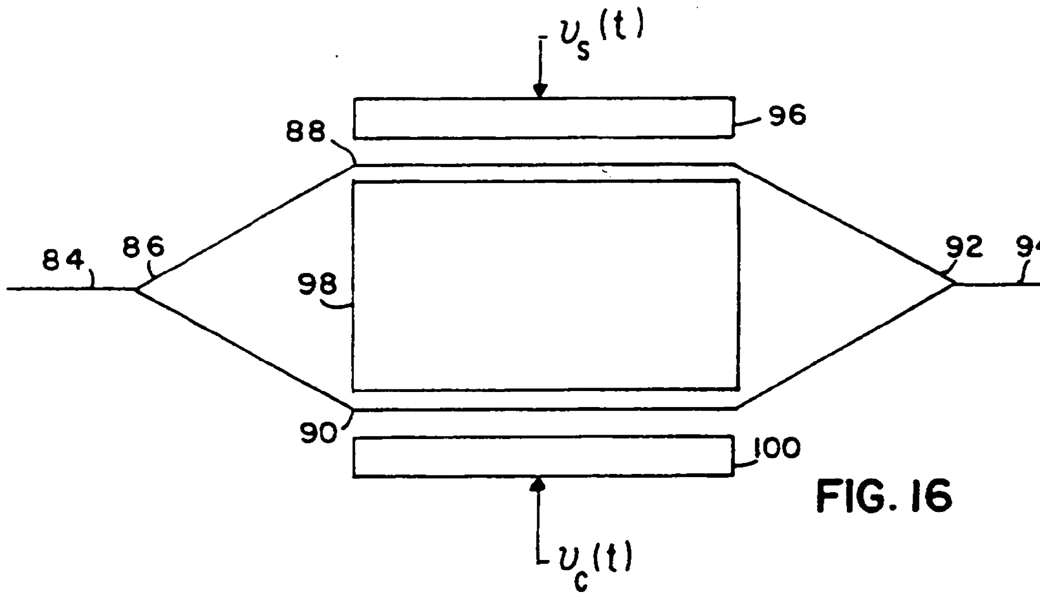
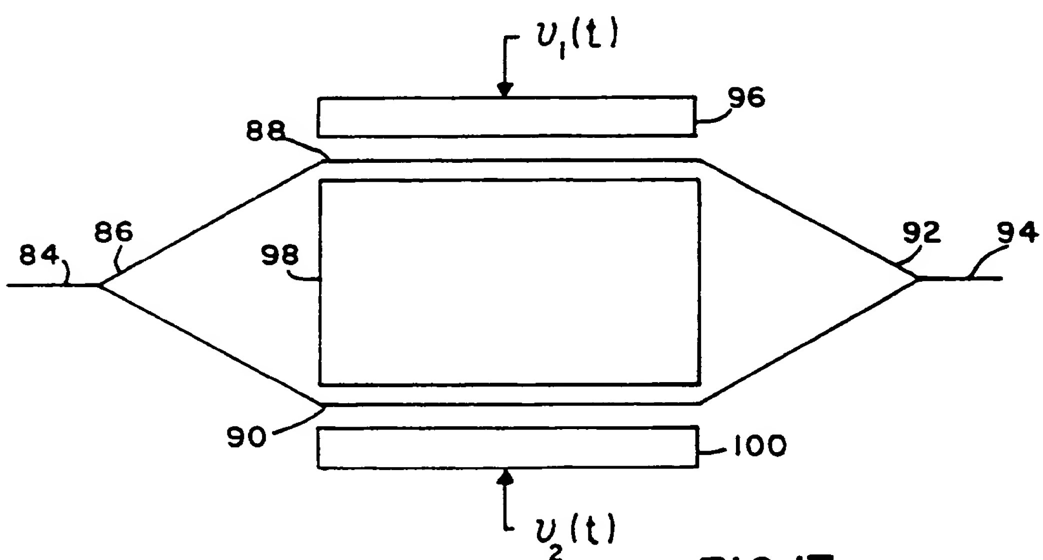

262
264
266
260
TUNABLE OPTICAL FILTER
PHOTODETECTOR
RECEIVER
TUNING VOLTAGE

FIG.15



$v_s(t)$
96
88
84
86
98
92
94
90
100
$v_c(t)$


FIG. 16



$v_1(t)$
96
88
84
86
98
92
94
90
100
$v_2(t)$


FIG. 17

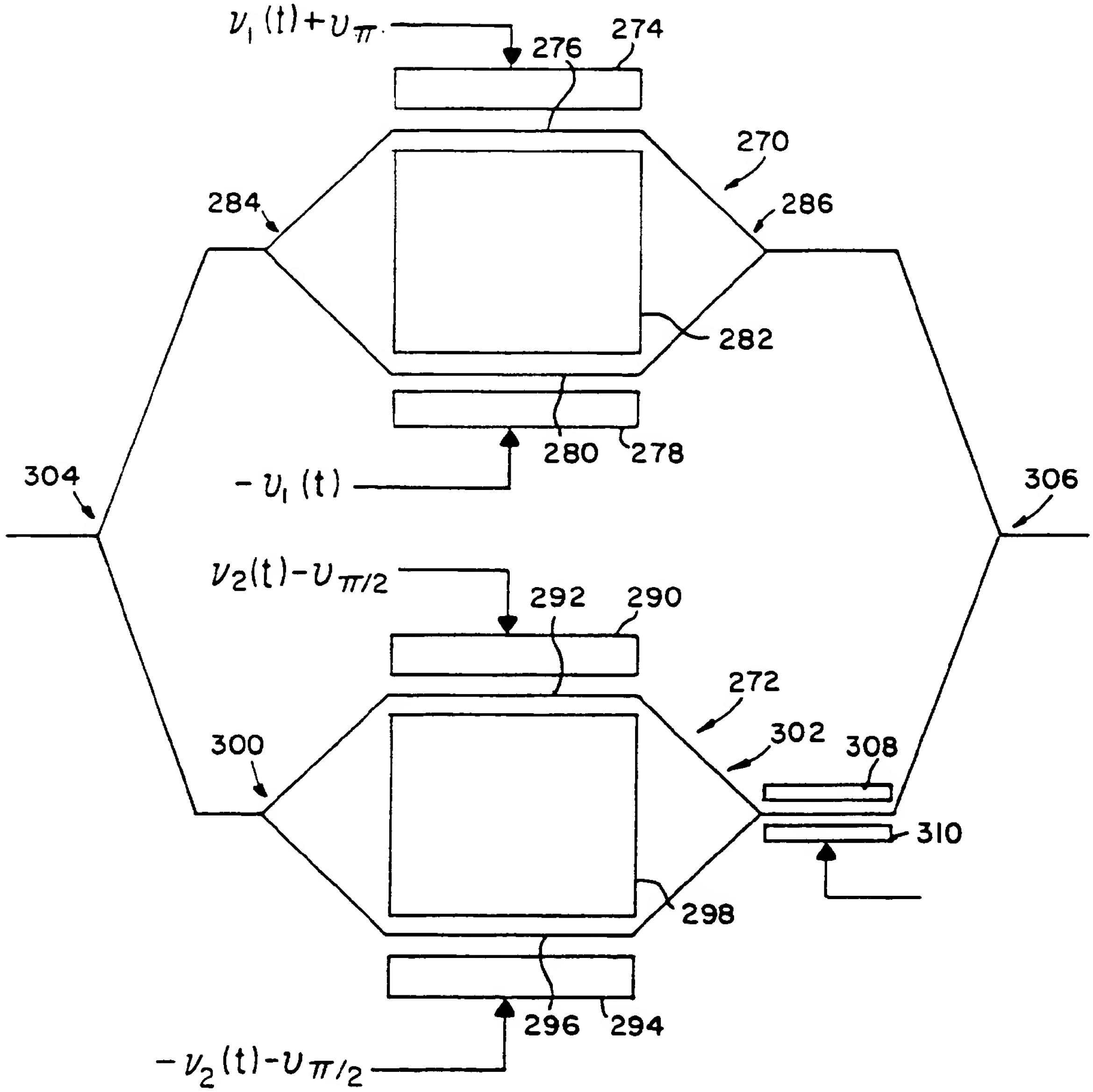

$\nu_1(t)+\upsilon_\pi$
276
274
270
284
286
282
280
278
$-\upsilon_1(t)$
304
306
$\nu_2(t)-\upsilon_{\pi/2}$
292
290
272
302
308
300
310
298
296
294
$-\nu_2(t)-\upsilon_{\pi/2}$

FIG.18

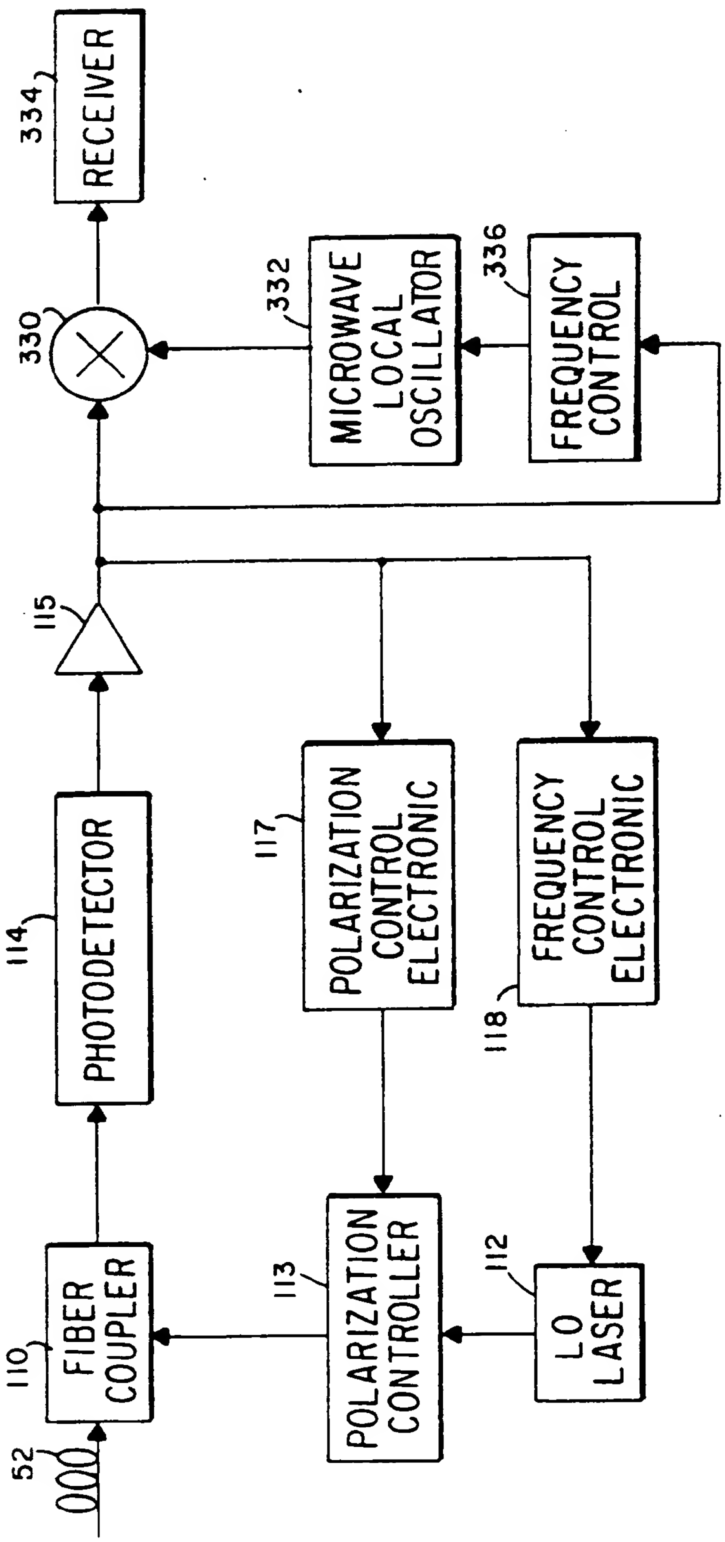

52
110
FIBER COUPLER
114
PHOTODETECTOR
115
330
334
RECEIVER
332
MICROWAVE LOCAL OSCILLATOR
336
FREQUENCY CONTROL
117
POLARIZATION CONTROL ELECTRONIC
118
FREQUENCY CONTROL ELECTRONIC
113
POLARIZATION CONTROLLER
112
LO LASER

FIG.19

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## (54) Quadrature optical phase modulators for lightwave systems.

(57) Optical communication methods and apparatus are disclosed for transmitting two or more optical signals with different optical carrier frequencies ($f_{01}$, $f_{c2}$) on a single optical fiber with high spectral efficiency. Each optical carrier is typically modulated with multiple modulated subcarriers. In one embodiment, an optical phase modulator provides cancellation of second order intermodulation products in each optical signal, thereby permitting the optical carrier frequencies to be spaced by $2f_{max}$, where $f_{max}$ is the maximum modulation frequency. In another embodiment, a single sideband optical phase modulator provides cancellation of second order inter-modulation products and one signal sideband, thereby permitting the optical carrier frequencies to be spaced by $f_{max}$. Quadrature optical phase modulators for simultaneous transmission of two independent baseband digital data signals or two independent subcarrier multiplexed signals are disclosed.

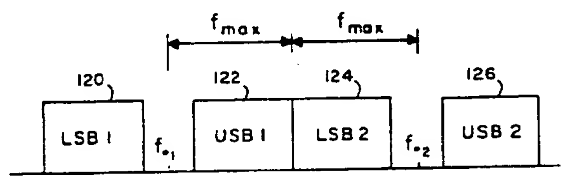


FIG.8

EP 0 496 298 A3

European Patent Office

# EUROPEAN SEARCH REPORT

Application Number

EP 92100754.8

## DOCUMENTS CONSIDERED TO BE RELEVANT

| Category | Citation of document with indication, where appropriate, of relevant passages | Relevant to claim | CLASSIFICATION OF THE APPLICATION (Int. Cl.5) |
|---|---|---|---|
| A | EP - A - 0 288 418 (KRONE) * Abstract; claim 1 * -- | 1-4,5, 9 | H 04 B 10/04<br>H 04 B 10/10<br>H 04 B 10/12<br>H 04 B 10/22 |
| A | EP - A - 0 128 297 (NEC) * Abstract; page 2; claim * ---- | 1-4,5, 9 | |

TECHNICAL FIELDS SEARCHED (Int. Cl.5)

H 01 S 3/00
H 04 B 9/00
H 04 L 9/00

The present search report has been drawn up for all claims

| Place of search | Date of completion of the search | Examiner |
|---|---|---|
| VIENNA | 14-01-1993 | BLASL |

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